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MINING AND GEOLOGICAL MODELS OF VIRTUAL COMPLEX ORE BLOCKS OF THE BENCH

Purpose. Creation of mining and geological models of virtual complex ore blocks of a bench to develop a basic methodology for determining the geological structure of complex structural sections of mineral deposits.

Methodology. In the scientific and technical substantiation of mining and geological, mining and technical indicators of complex structural blocks in terms of ore saturation and complexity of the morphological structure of blocks of ledges, methods of complex and abstract-logical analysis, synthesis, systematization, the method of theoretical generalization, generalization of information sources and world experience in the field of geoinformation of complex structural deposits, statistical analysis, mathematical modeling, mining and geological modeling of mineral deposits were applied.

Findings. Mining and geological models of virtual complex structure ore blocks (CSOB) of the bench have been created. The mining and geological characteristics of the blocks are analytically interconnected with the geometric parameters of the scattered ore bodies and the dimensions of the layer of admixed rock or lost ore. They determine the degree of complexity of the geological structure of the CSOB. According to the given sizes and location of disparate solid and dispersed ore bodies of virtual complex structural blocks, the numerical values of the mining and geological characteristics of ore blocks were calculated using the developed method. CSOB are subdivided into more ore-saturated, moderately ore-saturated, less ore-saturated as well as complex structural and more complex structural ones.

Originality. For the first time in mining, the concepts of "virtual complex-structural ore blocks of a bench" and "mining and geological models of virtual complex-structural ore blocks of a bench" have been introduced. The set of geometrical parameters of the scattered ore bodies of the block and their mining and geological characteristics are presented as mining and geological models of the virtual CSOB of the bench. The developed models make it possible to establish patterns of changes in the mining and geological characteristics of complex ore blocks.

Practical value. The developed mining and geological models of virtual complex structural blocks serve as the basis for creating mining and geological models of real complex ore blocks, models of CSOB in a blasted state. They will make it possible to develop a methodology for rationing losses and impoverishment of ores for real complex-structural blocks, to choose rational parameters for mining technologies for disparate ore bodies in specific mining and geological conditions, and to expand the use of waste-free, low-waste technologies in the development of complex-structural mineral deposits.

Keywords: *complex-structural ore blocks, ore saturation factor, mining and geological characteristics, models of virtual blocks*

Introduction. Complete extraction of minerals from the subsoil, including amenable ores, reduction in their losses and impoverishment during the exploitation of various deposits is one of the most acute and urgent problems of mining science and industry [1–5]. The problem acquires special significance in the development of complex structure ore deposits. The latter are usually represented by a diverse combination of ore bodies and host rocks (substandard ores) of complex configuration, size, and having different physical, technical and geological characteristics. Visually, contacts between standard and substandard ores are not visible and they are of a probabilistic nature. Their share in non-ferrous metallurgy enterprises of the CIS countries is 60–90 % and operational losses of ore can reach 20–35 % [6–8].

The main reasons for the appearance of a high level of losses and impoverishment in the open mining of complex-structural minerals are the insufficient knowledge of the geological and morphological structure of complex-structural blocks of benches, the mismatch of the technologies used for excavation and loading operations with the actual mining and geological conditions for the occurrence of complex-structural minerals in the massif and in the blasted state, the use of private methods for determining and normalizing losses and impoverishment, focused on mining and geological objects with clear geological boundaries – veins, lenses, layers and reservoir formations. Moreover, the quantitative and qualitative losses of minerals in them are usually established for the marginal areas of ore blocks.

In the software products Datamine, Surpac, Micromine, etc., widely used at mining enterprises, the problem of managing losses and dilution is considered on the scale of the entire deposit as a whole, and not in the context of a bench, a separate excavation unit (excavator entry). To adapt them to geological objects of a smaller scale (horizon, bench) of complex configuration and structure, it becomes necessary to create appropriate mining and geological, mathematical models that serve as the basis for developing methods for determining and normalizing operational quantitative and qualitative losses in real conditions of mineral development.

Naturally, the primary of these models is the mining and geological model of complex ore blocks of benches. It should explicitly depict ore bodies in various sections of the ledge (in transverse, longitudinal, horizontal) and places of loss and impoverishment of ores during their excavation from real complex-structural ore blocks (CSOB). Such a model can be created on the basis of mining and geological models of virtual complex ore blocks of benches. As the latter, typical complex structural mineral deposits with appropriate modernization can be considered. Mining and geological models of virtual complex structural blocks of the bench serve as the foundation for the development of a basic methodology for determining the geological and morphological structure of complex structures of mineral deposits. This technique, in turn, is the basis for creating new methods for determining losses and impoverishment in the development of any complex structured minerals. It contributes to the development and implementation of efficient technologies for extracting disparate ore bodies from heterogeneous faces using mining and geological, mathematical models of real complex-structural blocks of a bench.

Literature review. Deposits of ores of non-ferrous metals, noble and rare metals are mostly complex structures. Ore areas have a complex geological and morphological structure, uneven mineralization, visually indistinguishable boundaries with host rocks. They are characterized by different shapes, different sizes of ore bodies, their spatial distribution in the space under consideration, different mineralization and physical and mechanical properties of rocks [1–8]. The totality of these features determines the degree of complexity of the geological and morphological structure of complex structural areas of minerals.

To assess the geological and morphological structure of the CSOB of bench, its use for the effective development of these blocks, their mining and geological models are created. In the general case, the mining and geological model contains data on interval sampling of the core of exploratory wells in terms of the content of useful components, harmful impurities, information on the depths of the wells and the geometric parameters of scattered ore bodies. On the basis of these data, taking into account the requirements submitted by the consumer for salable ore, the boundaries between amenable and non-conditioned ores are established. Ore bodies are being delineated in the ore block of the bench.

For example, in [1] it is noted that three-dimensional geological modeling usually begins with spatial points, lines or surfaces, interpreted on the basis of available observations and measurements. The main data for building geological models are information about the surface of a quarry field, geological maps and sections, exploration data from boreholes, and geophysical measurements.

Numerical methods are used to determine the geometry of geological structures from disparate data:

1. Direct construction of geological boundaries (methods of explicit structural modeling). Each geological interface is determined by interpolation between nodes of a two-dimensional orientable graph. Because surfaces are embedded in 3D space, surfaces do not necessarily define a closed volume, and modeling involves projections of data points onto the surface.

2. Construction of a scalar function whose equipotential surfaces are the geological boundaries of interest. A scalar function can be viewed, for example, as the distance to a signed interface, or as a relative function of geological time.

Unfortunately, the ways of practical application of these methods to the construction of a geological model are not indicated in the work.

Article [2] describes a method for designing optimal ore boundaries for lateritic metal deposits. It minimizes ore dilution/waste and involves two main steps. The uncertainty at the ore body boundary is represented by a set of stochastic realizations generated using a multi-point statistics algorithm. The optimal ore body boundary is then determined using the model calibration method. Pilot points are synthetic height values and are used to build smooth boundaries using the multilevel B-spline method. The value of the generated surface is estimated using the expected sum of losses in each of the stochastic implementations. A process simulation algorithm is used to iteratively determine the set point values that minimize the expected loss.

The main advantage of the proposed method is the reduction in economic losses. The application of the method on bauxites showed much lower losses compared to real mining.

However, the proposed method for delineating ore bodies is not analytically formalized, and there are no examples of its direct application.

It is emphasized in [3] that the proper classification of Mineral Resources and Ore Reserves, as well as the corresponding prediction of the amount of impoverishment and ore loss, strongly influence subsequent mining activities. Two interrelated phenomena of ore dilution and loss are caused by the exploitation of blocks (selective mining units) with different geological and metallurgical characteristics (lithology, hydrothermal alteration, mineralogy, metal content in deposits, recoverable grade, recovery factor, etc.).

The correct prediction of the degree of dilution and loss of ore in each block can be achieved on the basis of exploration drilling data. Studies in this direction were carried out at the Gol-Goar iron ore mine (Iran). Conventional kriging with $10 \times 10 \times 15$ m blocks was applied to calculate the metal grade in a block based on 10,998 blastholes over a 5×5 m grid. In this way, the found content can be taken as true, with which the simulated content will be compared.

Given the complexity of the geometry of magnetite-bearing rock types, block models built on the basis of information about the metal content require taking into account the lithological factor. This approach is very important for understanding the type of an ore deposit and developing geological and geo-metallurgical models.

At the same time, stochastic modeling of both lithological boundaries and grades has a preference, which controls mineralization, highlights the boundaries between ore bodies and waste rocks. This is confirmed by comparing the simulated grades with the true grades obtained from blast hole information. Fewer classification errors affect projected ore tonnages and future mine plans. The article does not describe the algorithm for constructing a geological model of an ore block, methods for determining losses and dilution of ore, depending on the schemes of the geological model.

It is noted in [4] that 3D geological modeling is an emerging technology for studying geological structures, exploration for minerals, and quantifying mineral reserves. It includes three-dimensional models of the development of deposits of various genetic types and complexity of the geological structure, operational adjustment of geological models of deposits according to the degree of development of their reserves. The author has developed a geological model of the Galeshchinskoye field. The model makes it possible to estimate in advance the resources of the K22 ore deposit. The model does not take into account the geological structure of complex ore bodies.

Article [5] describes innovative approaches to geological modeling of alluvial deposits of the Poltava series in the Dnieper-Donetsk depression and the Ukrainian shield. A complex of information support is proposed, which includes two blocks: a predictive-paleoreconstructive retrospective-static model and a complex ecological-geological model of a local geological object. It provides a full cycle of forecasting, prospecting, exploration, exploitation, and environmentally safe extraction of minerals. A geological model of the Motronovsko-Annovskoye deposit of titanium-zirconium ores has been created. The model takes into account the spatial distribution of ore bodies, their relationship with the morphology of the ore sequence and lithological features (clay content, granulometric composition of sands, etc.). However, there is no analytical description of these relationships.

In [6], the relevance of accelerating scientific work aimed at the development and implementation of new technologies, processes and technical means that ensure a more complete extraction of all components contained in the ore into a commercial product is substantiated. It is proved that such results are achieved with full compliance of ore processing technologies with its natural properties and technological characteristics in the rock mass.

In the article [7], a study on the geological structure and conditions of industrial development of a typical deposit of the Azov block of the Ukrainian shield was carried out. Threshold parameters for modeling and calculation of iron ore reserves are substantiated. The Leapfrog program implements a geostatistical calculation of reserves. The spatial distribution of the magnetic iron content within the ore deposit was estimated and a statistical analysis of the simulation data was carried out. The basic onboard parameters for calculating iron ore reserves are substantiated. A block model of the field was created with justified geological and industrial parameters. At the same time, the model lacks information about the complexity of the geological structure of ore bodies.

In [8], data are given on the geological and morphological structure of copper deposits in Kazakhstan Bozshakol and Aktogay, their impact on the level of quantitative and qualitative losses of ore.

The paper [9] describes the experience of creating a geological model of the Glavitsa mine field. To model the geological structure of the ore body, the Surpac v.6.2 program was used, which allows for a qualitative and quantitative assessment of nickel deposits in Kosovo.

The division of nickel reserves into mini-blocks of 25 × × 25 m and 50 × 50 m using deep geological wells made it possible to correctly assess the quality of silicate ore at the deposit. At the same time, the contacts of the roof and soil of the ore body, the mutual arrangement of clay layers within the ore body were also determined. According to the transverse geological profiles, the average percentage of nickel and related components was determined (estimated) at each horizon, starting from the horizon of 595 m. They were reflected in the geological model of the deposit. However, there is no information on the layout of ore bodies and their geometrical parameters.

Article [10] describes the practical use of long-term geometallurgical models in mining planning, including simulation models. The latter make it possible to take into account the spatial variability of minerals in a quarry field using the stochastic DBS approach and to set mining periods for each ore block. Based on the factors at play, the most profitable blocks are mined first to optimize the throughput of the quarry over the life of the pit. The use of direct block planning models makes it possible to develop mining schedules for all areas, to control the stripping rate for the entire period of the open pit operation. The geo-metallurgical approach covering all process variables is fundamental to improving the efficiency of the development of various minerals, including the fuller recovery of useful components. Unfortunately, the essence of geological modeling of minerals has not been disclosed.

In [11], it is stated that the geological control of the physical and chemical properties of ore deposits is important for modeling the spatial distribution of minerals with different mining and geological characteristics. The problem is solved using the method of stochastic modeling. It consists in interpreting geological data at a particular location as a result of a discrete random variable. This probabilistic approach takes into account the fact that the geology at any location cannot be accurately known from drilling data. All available information, including statistical data, is aimed at obtaining the most realistic models of the field. For this, it becomes necessary to use an approach based on Markov random fields and computer graphics methods that reproduce multipoint images. They will replace the two-point semivariogram with a training image. The latter is a geological analogue of the deposit, which describes the geometric aspects of the position of the rocks.

Multi-point modeling provides a practical opportunity to assess the uncertainty in the geological structures of individual blocks of the field. The generated realizations will be comparable to the existing geological model of the considered field. However, such data and comparisons are not provided in the article.

In geology, as noted in [12], little attention is paid to the creation of 3D models of deposits. To fill this gap, a new approach is proposed to study the regularities of mineralization in a given field. This approach is based on lithology data of individual elements and allows complex analysis of structural patterns at the field scale.

It is a powerful "outside" method for deciphering the geometry of mineral deposits using the most available 3D data – well drilling. Structural features that will be visible in the outcrop can be predicted using the "outside-in" method.

The interpretation of data from the Sigma-Lamaak gold deposit based on such a model has been tested in the field and shows satisfactory results. It will help predict the nature of mineralization in poorly explored deposits and their reserves. In this case, the distribution of various ores is understood as their structural and geological patterns. Mineral resource boundaries will be understood in the context of structural architecture. However, these interpretations are not supported by the structure and elements of the proposed 3D field model.

The article [13] describes the experience of 3D modeling of a gold deposit in Shangong. The 3D geology model aims to identify potential targets and estimate mineral resources using the GOCAD software. The results show the following: 1) zones of high gold value are associated with intrusion and cross fault structures of the NNE; 2) blocks of high gold values of the Au/Pb ratio can be used to depict mineralization zones; 3) conventional kriging and DSI methods can show the trend of the attribute model; 4) simulation results can characterize the uncertainty of the 3D model through uncertainty analysis.

Conditional modeling is also suitable for quantifying uncertainty within blocks. In this sense, the classification of Mineral Resources based on the implementations obtained leads to a plausible calculation of robust extraction functions showing worst-case and best-case scenarios. However, the application of proper geostatistical modeling algorithms is critical when modeling variables with a strong cross-correlation structure. Unfortunately, these advantages of the method have not found adequate evidence.

The paper [14] notes the role of GIS-based Mineral Prospect Mapping (MPM). It is an automated methodology for delimiting and better limiting target areas that are considered promising for a particular type of mineral deposit. However, the MPM, which is a multi-faceted and multi-criteria approach, faces a high degree of uncertainty. Uncertainties associated with the data (for example, sometimes erroneous, inadequate, incomplete, unevenly distributed, or poorly resolved nature of the input data); model-related (e.g., diversity and inherent natural variability of mineral deposits, lack of complete knowledge of the target type of mineral deposit, ability to interpret geoscience datasets); judgment-related (e.g., the impact of cognitive heuristics and bias).

They can be leveled using carefully validated high quality input data, developing target models based on the best possible understanding of the underlying mineral deposit model, and implementing advanced techniques such as deep learning algorithms.

Future work in MPM and related areas should focus on gaining a deeper understanding of the main components expressing the ore formation process, collecting and using high quality data, developing advanced mining methods, and integrating forecast maps. This work, together with the development of advanced machine learning tools, contributes to the reduction of these uncertainties.

The article [15] discusses the general concepts of integrated geostatistical modeling with a special focus on blast design, equipment selection and related ore loss quantification, ore dilution. The appendix describes the integration of geostatistically modeled grade models, geologic and geomechanical models with blast modeling to provide a link between estimated pre-blast and post-blast ore body properties.

Although a very specific explosion simulation process was used in this study, it can be replaced by any other type of simulation.

In [16], a new approach to the analytical determination of the location of heterogeneous rocks in the collapse is presented. It will form the basis for creating a model of complex-structural ore blocks in an exploded state.

Thus, the review and analysis of published materials on the geological modeling of mineral deposits confirm the importance and relevance of the problem. At the same time, insufficient attention has been paid to the modeling of ore blocks in benches. It is well known that recommendations to reduce the loss and impoverishment of minerals are based on them. Therefore, the development of mining and geological models of the CSOB, in particular, the virtual CSOB of the bench, is a very necessary and unique action.

The purpose of the article is to create mining and geological models of virtual complex-structural ore blocks of a bench for the development of a basic methodology for determining the geological structure of complex-structural mineral deposits.

Research objectives are:

- analysis of literature data on the modeling of mineral deposits;

- new typification of complex ore blocks of the bench;
- substantiation of the concept of virtual CSOB of bench;
- substantiation of the method for determining the mining and geological characteristics of the CSOB;
- development of a basic methodology for determining the complexity of the geological structure of the CSOB;
- creation of mining and geological models of virtual CSOB;
- the prospect of using new mining and geological models to manage the quantitative and qualitative losses of minerals during their open development.

Description of the technique. To solve the tasks set, mining and geological models of virtual complex structural blocks of the bench were created. As the latter, blocks are taken made of fixed scattered solid and dispersed ore bodies of a given quality of various shapes and sizes with straight-line contacts with rock interlayers. The mining and geological characteristics of the blocks are analytically interconnected with the geometric parameters of the scattered ore bodies and the dimensions of the layer of admixed rock or lost ore. The developed mining and geological models of virtual CSOB are a set of geometric parameters of the scattered ore bodies of the block and their mining and geological characteristics. With their use, the degree of complexity of the geological structure of the CSOB of bench and their classification according to the complexity of the geological and morphological structure are established.

Scientific novelty. For the first time in mining, the concepts of "virtual complex-structural ore blocks of a bench" and "mining and geological models of virtual complex-structural ore blocks of a bench" were introduced. Virtual complex-structural ore blocks are taken to be those composed of fixed disparate solid and dispersed ore bodies with specified mining and geometric parameters. It is substantiated that the set of geometrical parameters of the scattered ore bodies of the block and their mining and geological characteristics represent the mining and geological models of the virtual CSOB of the bench. The developed models serve as a basis for establishing patterns of changes in the mining and geological characteristics of complex ore blocks.

Presentation of the main material and the results obtained. The issues of assessing the geological and morphological structure of complex-structural deposits in order to ensure rational selective extraction of mineral have always been in the focus of attention of scientists in Kazakhstan, near and far abroad [1–10]. They proposed to determine the degree of slaughtering complexity by the number of ore and rock layers, their thickness and angle of incidence, as well as the number of grades of ore mass requiring separate excavation. Based on these prerequisites, deposits of non-ferrous metal ores, which have a complex geological and morphological structure and are developed by an open method, are divided into four types [6, 7]. They are shown graphically in Fig. 1.

The benches of the first type of deposits "a" are assumed to consist of one ore body and one layer of host rocks of different thickness, having small angles of inclination. The benches of the second type "b" contain two or three ore bodies of sloping and gently sloping occurrence, separated by host rocks. The benches of the third type "c" include several steeply dipping ore bodies. The fourth type of benches "d" contains ore bodies in the form of nests and lenses.

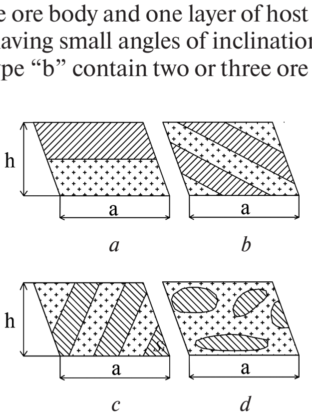

Fig. 1. Types of complex structural bench blocks: h – block height; a – block width; ▨ *– ore;* ⁘ *– solid*

The analysis of these and other literary sources, their theoretical understanding shows that, according to the nature of the location of ore bodies and their geometric parameters, the complex blocks of benches can generally be divided into only two types [6].

In the new approach to the typification of complex-structural ore blocks in benches, ore bodies are understood as the volumes of amenable ore reserves established by the results of analysis of blasthole samples and other geophysical methods. They do not always coincide with the balance reserves of ores, since they are revealed as a result of additional exploration. It is also assumed that the rock layers contain substandard ores in their composition.

In the new typification, blocks composed of disparate solid ore bodies of various shapes and sizes with straight-line contacts with rock interlayers are assigned to the first type of CSOB of bench (Fig. 2). The latter is due to the fact that when using software products Datamine, Surpac, Micromine, etc., only straight-line contacts take place. They extend from one block boundary (excavation unit) to another and form angles with the horizon varying from 0 to π.

In a particular case, the first type of CSOB of bench can be represented by horizontal, inclined or vertical layer-like ore bodies of relatively consistent thickness (contact lines are parallel) or lenticular inclusions of variable thickness, between which interlayers of host rocks are located.

The second type of CSOB of bench is represented by blocks composed of dispersed ore bodies in the form of geometric figures of various shapes and sizes, for example, polygons with straight-line contacts with host rocks (Fig. 3). Con-

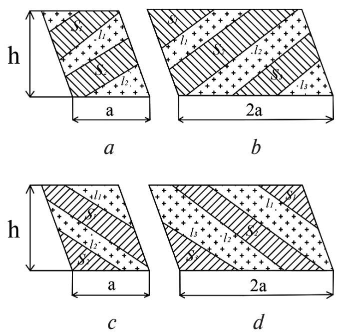

Fig. 2. Types of complex structural blocks of ledges composed of disparate solid ore bodies: h is the height of the block, a and 2a are the width of the block, S_i is the area of the i^{th} ore body, l_i is the length of the contact lines of the i^{th} ore body with host rocks

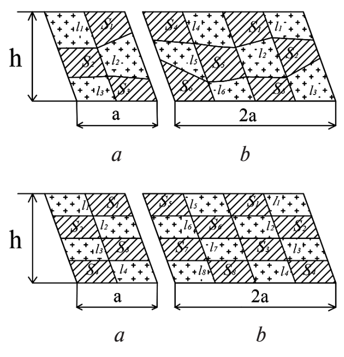

Fig. 3. Types of complex structural blocks composed of dispersed ore bodies: h is the block height, a and 2a are the block width, S_i is the area of the i^{th} ore body, l_i is the length of contact lines of the i^{th} ore body with host rocks

tact lines are located inside the block (excavation unit). In a particular case, this type of complex structural blocks may consist of nested ore bodies of various shapes and sizes, etc. The mutual arrangement of ore bodies in the block is virtual.

The theoretical analysis of the above types of CSOBs (Figs. 2, 3) shows that, with an appropriate quantitative assessment of their technological characteristics, they can be considered as a prototype of virtual complex-structural ore blocks of benches, composed, respectively, of separate continuous and dispersed ore bodies. To prove this assumption, it is necessary that the desired generalized technological characteristics of the CSOB analytically interconnect all the identified geometric parameters of the geological and morphological structure of the blocks. Only in this case, they will objectively reflect the natural state of the object under study and contribute to a more complete extraction of minerals from the bowels through the appointment of the most effective technologies for drilling and blasting and excavation and loading operations in the conditions of specific complex structural blocks.

As the required mining and geological characteristics, the most common and relatively easily measured quantities are considered:

- the block ore saturation factor;
- the coefficient of complexity of the geological structure of the block.

The block ore saturation factor (k_{sf}) is calculated by the formula

$$k_{sf} = \sum_{i=1}^{n} S_i \Big/ S_b, \qquad (1)$$

where S_i is the cross-sectional area of the i^{th} ore body on the given section of the block, m^2; S_b is the area of the considered section of the complex structure block, m^2; n is the number of ore bodies.

The average ore saturation coefficient for the entire complex structure block is determined by the dependence

$$k_{sf}^{av} = \frac{1}{m} \sum_{\gamma=1}^{m} \left(\sum_{i=1}^{n} S_i \Big/ S_b \right). \qquad (2)$$

Here, m is the number of cuts; γ is the designation of the current block cut.

The number of sections depends on the length of the complex structure block. Each section covers a zone with a length equal, as a rule, to the distance between boreholes in a row.

According to this indicator, complex structural blocks are divided into:

- more ore- saturated (k_{sf} = 0.75–0.6);
- moderately ore-saturated (k_{sf} = 0.6–0.4);
- less ore-saturated (k_{sf} = 0.4–0.25).

The coefficient of complexity of the geological structure of the block (k_{co}) is determined by the dependence

$$k_{co} = \sum_{i=1}^{n} l_i t \Big/ \sum_{i=1}^{n} S_i, \qquad (3)$$

where l_i is the length of the contact lines of the i^{th} ore body with host rocks (or substandard ores) in this section, m; t is the thickness of the layer of host rocks (or ores) that fall into the ore mass (or into the shipped rock) during excavation, m; S_i is the cross-sectional area of the i^{th} ore body in this section of the block, m^2; n is the number of ore bodies.

According to dependence (3), with the exclusion of the signs of the sum from it, the coefficient of complexity of the structure of the i^{th} ore body in the block is determined.

$$k_{co} = \mu \left(\sum_{i=1}^{n} l_i \Big/ \sum_{i=1}^{n} S_i \right), \qquad (4)$$

where μ is some coefficient of proportionality, m. In a particular case, $\mu = t$.

According to this indicator, complex structural blocks are divided into:

- complex structure (k_{co} = 0.1–0.2);
- more complex structure (k_{co} = 0.2–0.3).

The set of geometric parameters of disparate ore bodies of bench blocks (Figs. 2, 3) and mining and geological characteristics (k_{sf}, k_{co}), interconnecting the geometric dimensions (S_i, l_i) of ore bodies, can be considered as mining and geological models of virtual CSB, composed of scattered solid and dispersed ore bodies. The design of these models is shown in Fig. 4.

At the same time, the mining and geological characteristics of complex structural ore blocks serve as a criterion for classifying CSOB according to the complexity of their geological structure. They are subdivided only into two groups: complex-structural and more complex-structural. As estimates show, these gradations are valid for real complex structural minerals. Therefore, the methodology for determining the geological structure of the CSOB is called the basic one. This result is shown schematically in Fig. 5.

In order to reveal in more detail the essence of the proposed models and methods for determining the geological structure of complex-structural areas of minerals, we will analyze the numerical values of the mining and geological characteristics of the considered CSOB. In calculations, the height of the blocks is taken equal to the height of the ledge, i.e. h = 10 m, block widths are equal to a = 9 and $2a$ = 18 m. The areas of ore bodies S_i (m^2) and the lengths of contact lines of ore bodies with host rocks (or substandard ores) l_i (m) were taken close to those in non-ferrous metallurgy quarries in the CIS countries.

The mining and geological characteristics of the considered virtual complex structural blocks (k_{sf}, k_{co}) with known S_b, S_i, l_i were calculated by formulas (1, 3) using the AutoCAD program. In AutoCAD, after drawing sections of complex structural blocks according to the known given data, using the special built-in utility "Measure", the necessary section of the block is selected and its area (m^2) and the length of contact lines (m) are measured. Their values are given in Tables 1 and 2. The same tables contain the values of the coefficients of complexity of the structure of individual ore bodies and blocks as a whole for options "*a*", "*b*", "*c*", "*d*". The variants differ from each other in that they contain ore bodies of various configurations, sizes, and various mutual arrangements (Figs. 2, 3).

The analysis of the data in Tables 1, 2 shows that both ore blocks are moderately ore-saturated (k_{sf} = 0.427–0.539) and complex-structured (k_{co} = 0.139–0.193). The exception is CSOB composed of dispersed ore bodies, options "*c*" and "*d*", for which k_{co} = 0.209–0.238. These blocks are more com-

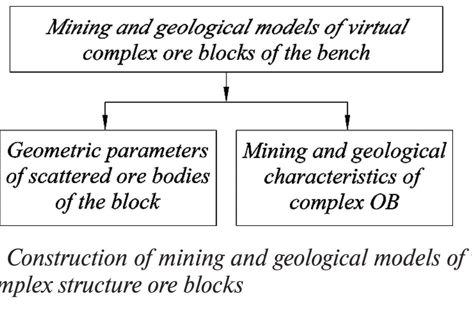

Fig. 4. Construction of mining and geological models of virtual complex structure ore blocks

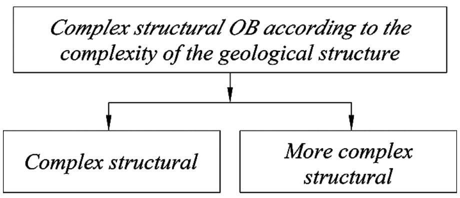

Fig. 5. Classification of CSOB according to the complexity of the geological structure with their fixed ore saturation

Table 1

Mining and geological characteristics of CSOB composed of scattered solid ore bodies

a	*b*	*c*	*d*
$S_1(l_1) = 21.12$ (13.25)	$S_1(l_1) = 17.69$ (7.64)	$S_1(l_1) = 34.43$ (23.89)	$S_1(l_1) = 13.23$ (8.69)
$S_2(l_2) = 26.93$ (15.94)	$S_2(l_2) = 50.09$(28.23)	$S_2(l_2) = 13.89$ (8.92)	$S_2(l_2) = 44.29$(33.48)
	$S_3(l_3) = 29.35$ (18.17)		$S_3(l_3) = 19.34$ (10.54)
$\sum S_i\left(\sum l_i\right)=48.05\left(29.19\right)$	$\sum S_i\left(\sum l_i\right)=97.13\left(54.04\right)$	$\sum S_i\left(\sum l_i\right)=48.32\left(32.81\right)$	$\sum S_i\left(\sum l_i\right)=76.86\left(52.71\right)$
$k_{co} = 0.157$, $k_{co} = 0.148$	$k_{co} = 0.108$, $k_{co} = 0.141$, $k_{co} = 0.155$	$k_{co} = 0.173$, $k_{co} = 0.160$	$k_{co} = 0.164$, $k_{co} = 0.189$, $k_{co} = 0.136$
$k_{sf} = 0.534$, $k_{co} = 0.152$	$k_{sf} = 0.539$, $k_{co} = 0.139$	$k_{sf} = 0.536$, $k_{co} = 0.169$	$k_{sf} = 0.427$, $k_{co} = 0.171$

Table 2

Mining and geological characteristics of CSOB composed of dispersed ore bodies

a	*b*	*c*	*d*
$S_1(l_1) = 14.59$ (8.58)	$S_1(l_1) = 15.52$ (11.5), $S_2(l_2) = 14.50$ (13.58)	$S_1(l_1) = 11.25$ (7.16)	$S_1(l_1) = 11.25$ (9.82), $S_2(l_2) = 11.25$ (11.66)
$S_2(l_2) = 14.41$ (12.20)	$S_3(l_3) = 12.01$(10.3), $S_4(l_4) = 14.95$(8.39)	$S_2(l_2) = 11.25$ (11.66)	$S_3(l_3) = 11.25$ (14.32), $S_4(l_4) = 11.25$(7.16)
$S_3(l_3) = 12.08$ (7.64)	$S_5(l_5) = 17.25$(16.95), $S_6(l_6) = 15.10$(8.19)	$S_3(l_3) = 11.25$ (11.66)	$S_5(l_5) = 11.25$(7.16), $S_6(l_6) = 11.25$(14.32)
		$S_4(l_4) = 11.25$ (7.16) $\sum S_i (\sum l_i) = 45$ (37.64)	$S_7(l_7) = 11.25$(11.66), $S_8(l_8) = 11.25$(9.82)
$\sum S_i\left(\sum l_i\right)=41.08\left(28.42\right)$	$\sum S_i\left(\sum l_i\right)=89.33\left(68.91\right)$		$\sum S_i\left(\sum l_i\right)=90\left(85.92\right)$
$k_{co} = 0.147$, $k_{co} = 0.212$, $k_{co} = 0.158$	$k_{co} = 0.185$, $k_{co} = 0.235$, $k_{co} = 0.215$, $k_{co} = 0.14$, $k_{co} = 0.245$, $k_{co} = 0.135$	$k_{co} = 0.159$, $k_{co} = 0.260$, $k_{co} = 0.260$, $k_{co} = 0.159$	$k_{co} = 0.218$, $k_{co} = 0.259$, $k_{co} = 0.318$, $k_{co} = 0.159$, $k_{co} = 0.159$, $k_{co} = 0.318$, $k_{co} = 0.259$, $k_{co} = 0.218$
$k_{sf} = 0.456$, $k_{co} = 0.173$	$k_{sf} = 0.496$, $k_{co} = 0.193$	$k_{sf} = 0.500$, $k_{co} = 0.209$	$k_{sf} = 0.500$, $k_{co} = 0.238$

plex. Blocks of the second type have a relatively higher value k_{co} = (0.173–0.238) than blocks of the first type (k_{co} = 0.139–0.171). This predetermines a higher level of quantitative and qualitative losses of minerals in blocks of the second type, which is quite natural.

The highest value of k_{co} is found in ore bodies S_2, S_3 (k_{co} = = 0.260) of block "*c*" and ore bodies S_3, S_6 (k_{co} = 0.318) of block "*d*" of the second type of CSOB. In other words, during the extraction of these ore bodies from the CSB faces, the quantitative and qualitative losses are 26.0 and 31.8 %, respectively.

These research results confirm that the mining and geological characteristics of complex structure ore blocks of benches, justified above – the ore saturation coefficient and the indicator of the complexity of the geological structure, are objective criteria for their assessment in the open mining of complex structure minerals. These characteristics successfully interconnect the geometric dimensions and location of ore bodies in a given space and examples of their excavation from the CSOB. They represent a key element of mining and geological models of virtual complex ore blocks of benches.

Conclusions and prospects for further development of the direction. It has been substantiated that complex-structural ore sections of benches can be represented as blocks composed of disparate solid ore bodies of a given quality of various shapes and sizes with straight-line contacts with rock interlayers and blocks composed of dispersed ore bodies of various configurations and sizes. These blocks are taken as virtual.

It is proved that the mining and geological characteristics of virtual complex structural ore blocks – the ore saturation factor and the index of complexity of the geological structure, are objective criteria for their assessment in the open mining of complex structure mining. These characteristics successfully interconnect the geometric parameters of the ore bodies and the methods of their excavation from the CSOB.

The developed mining and geological models of virtual complex structural blocks, composed of scattered ore bodies of a fixed quality, allow, according to the given sizes and location of the ores of the bodies:

- calculating the ore saturation factor of ore blocks;
- classifying complex structural blocks by ore saturation;
- determining the complexity factor of the structure of individual ore bodies in the block;
- determining the coefficient of complexity of the geological structure of a complex structure block;
- creating a basic methodology for determining the geological structure of the CSOB;
- classifying complex structural blocks according to the geological and morphological structure of ore bodies.

Numerical values of the indicated characteristics are given for four variants of virtual CSOB. Based on them, the classification of complex structural blocks was carried out. It was revealed that both ore blocks are moderately ore-saturated (k_{sf} = 0.427–0.539) and complex structure (k_{sf} = 0.139–0.193). The exception is CSOB composed of dispersed ore bodies (options "*c*" and "*d*", for which k_{co} = 0.209–0.238). They belong to more complexly structured blocks.

The developed mining and geological models of virtual complex structural blocks serve as the basis for creating mining and geological models of real complex ore blocks. They will allow:

- predicting and normalizing losses and dilution of ores during the development of CSOB;
- creating mining and geological models of real complex structure ore blocks;

- creating models of CSOB in the exploded state;
- developing a methodology for normalizing losses and impoverishment of ores for real complex structure OB;
- choosing rational parameters for excavation technologies for disparate ore bodies in specific mining and geological conditions;
- expanding the use of low-waste technologies in the development of complex-structural mineral deposits.

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References.

1. Wellmann, F., & Caumon, G. (2018). 3-D Structural geological models: Concepts, methods, and uncertainties. *Advances in geophysics 59*, 1-121, Elsevier. https://doi.org/10.1016/bs.agph.2018.09.001.
2. Dagasan, Y., Renard, P., Straubhaar, J., Erten, O., & Topal, E. (2019). Pilot point optimization of mining boundaries for lateritic metal deposits: Finding the trade-off between dilution and ore loss. *Natural Resources Research*, *28*, 153-171. https://doi.org/10.1007/s11053-018-9380-9.
3. Masoumi, I., Kamali, G., Asghari, O., & Emery, X. (2020). Assessing the impact of geologic contact dilution in ore/waste classification in the Gol-Gohar Iron Ore Mine, Southeastern Iran. *Minerals*, *10*(4), 336. https://doi.org/10.3390/min10040336.
4. Vasiukhina, D. (2020). 3D geological modeling for mineral resource assessment of the Galeshchynske iron ore deposit, Ukraine. *Geoinformatics: Theoretical and Applied Aspects, 2020*(1), 1-5.
5. Remezova, O. O., Khrushchov, D. P., Vasylenko, S. P., & Yaremenko, O. V. (2021). Innovative approaches to information modeling of placer deposits. *Geoinformatics*, *2021*(1), 1-6.
6. Rakishev, B. R. (2017). Technological resources for improving the quality and completeness of use of the mineral raw materials. *News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technical sciences*, *2*(422), 116-124.
7. Bala, G., Kurylo, M., & Virshylo, I. (2022, November). Modeling and Estimation of Iron Ore Reserves in the Leapfrog on the Example of the Azovsky Block Deposit. In *16th International Conference Monitoring of Geological Processes and Ecological Condition of the Environment*, *2022*(1), 1-5. EAGE Publications BV.
8. Rakishev, B.R. (2019). Development of the Bozshakol and Aktogay copper ore deposits in Kazakhstan. *Gornyi Zhurnal, 2019*(1), 89-92. https://doi.org/10.17580/gzh.2019.01.18.
9. Zeqiri, R. (2021). Nickel discretization and quality review in Gllavica mine, Kosovo. *Mining of Mineral Deposits*, *15*(1), 35-41. https://doi.org/10.33271/mining15.01.035.
10. Morales, N., Seguel, S., Cáceres, A., Jélvez, E., & Alarcón, M. (2019). Incorporation of geometallurgical attributes and geological uncertainty into long-term open-pit mine planning. *Minerals*, *9*(2), 108. https://doi.org/10.3390/min9020108.
11. Osterholt, V., & Dimitrakopoulos, R. (2018). Simulation of orebody geology with multiple-point geostatistics – application at Yandi channel iron ore deposit, WA, and implications for resource uncertainty. *Advances in applied strategic mine planning*, 335-352. https://doi.org/10.1007/978-3-319-69320-0_22.
12. Cowan, E. J. (2020). Deposit-scale structural architecture of the Sigma-Lamaque gold deposit, Canada – insights from a newly proposed 3D method for assessing structural controls from drill hole data. *Mineralium Deposita*, *55*(2), 217-240. https://doi.org/10.1007/s00126-019-00949-6.
13. Jin, X., Wang, G., Tang, P., Hu, C., Liu, Y., & Zhang, S. (2020). 3D geological modelling and uncertainty analysis for 3D targeting in Shanggong gold deposit (China). *Journal of Geochemical Exploration*, *210*, 106442. https://doi.org/10.1016/j.gexplo.2019.106442.
14. Zuo, R., Kreuzer, O. P., Wang, J., Xiong, Y., Zhang, Z., & Wang, Z. (2021). Uncertainties in GIS-based mineral prospectivity mapping: Key types, potential impacts and possible solutions. *Natural Resources Research*, *30*, 3059-3079. https://doi.org/10.1007/s11053-021-09871-z.
15. Dowd, P. A., & Dare-Bryan, P. C. (2018). Planning, designing and optimising production using geostatistical simulation. *Advances in applied strategic mine planning*, 421-449. https://doi.org/10.1007/978-3-319-69320-0_26.
16. Rakishev, B., Rakisheva, Z., Auezova, A., & Orynbay, A. (2022). Automated determination of rock crushing zones in the collapse. *Mining of Mineral Deposits*, *16*(3), 109-114. https://doi.org/10.33271/mining16.03.109.

Гірничо-геологічні моделі віртуальних складноструктурних рудних блоків уступу

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Мета. Створення гірничо-геологічних моделей віртуальних складноструктурних рудних блоків уступу для розробки базової методики визначення геологічної будови складноструктурних ділянок родовищ корисних копалин.

Методика. При науково-технічному обгрунтуванні гірничо-геологічних, гірничо-технічних показників складноструктурних блоків за рудонасиченістю та складністю морфологічної будови блоків уступів застосовувалися методи комплексного та абстрактно-логічного аналізу, синтез, систематизація, метод теоретичного узагальнення, узагальнення інформаційних джерел і світового досвіду в галузі геоінформації складноструктурних родовищ, статистичний аналіз, математичне моделювання, гірничо-геологічне моделювання родовищ корисних копалин.

Результати. Створені гірничо-геологічні моделі віртуальних складноструктурних рудних блоків (РСРБ) уступу. Гірничо-геологічні характеристики блоків аналітично взаємопов'язані з геометричними параметрами розрізнених рудних тіл і розмірами шару породи, що домішується, або руди, що втрачається. Вони визначають рівень складності геологічної будови РСРБ. За заданими розмірами й розташуванням розрізнених суцільних і розосереджених рудних тіл віртуальних складноструктурних блоків за розробленою методикою обчислені чисельні значення гірничо-геологічних характеристик рудних блоків. РСРБ підрозділені на більш рудонасичені, помірно рудонасичені, менш рудонасичені та складноструктурні й більш складноструктурні.

Наукова новизна. Уперше в гірничій справі запроваджені поняття «віртуальні складноструктурні рудні блоки уступу» та «гірничо-геологічні моделі віртуальних складноструктурних рудних блоків уступу». Сукупність геометричних параметрів розрізнених рудних тіл блоку та їх гірничо-геологічних характеристик представлена як гірничо-геологічні моделі віртуальних РСРБ уступу. Розроблені моделі дозволяють встановлювати закономірності зміни гірничо-геологічних характеристик складних рудних блоків.

Практична значимість. Розроблені гірничо-геологічні моделі віртуальних складноструктурних блоків є базою для створення гірничо-геологічних моделей реальних складноструктурних рудних блоків, моделей РСРБ у підірваному стані. Вони дозволять розробити методику нормування втрат і збіднення руд для реальних складноструктурних блоків, вибрати раціональні параметри технологій виїмки розрізнених рудних тіл у конкретних гірничо-геологічних умовах, розширити масштаби використання безвідходних, маловідходних технологій при розробці складноструктурних родовищ корисних копалин.

Ключові слова: *складноструктурні рудні блоки, коефіцієнт рудонасиченості, гірничо-геологічні характеристики, моделі віртуальних блоків*

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